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PL.3: Vacuum Electronics and the World Above 100 GHz

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Introduction
Devices operating at frequencies above 100GHz have been an area of intense development recently within both the solid-state and vacuum electronics worlds. This talk will discuss some of the recent results in both electronic domains and considers salient features of some applications which are creating an opportunity for vacuum electronics to once again be an enabling technology for extending the available frequency space.

Why do we Need Systems Operating over 100 GHz?
There are many examples of plots of atmospheric attenuation represented in the literature that, to greater or lesser extents, show that as frequency of operation increases, attenuation appears to be difficult to overcome. Figure 1 shows an example[i]. Two major points are made clear by this chart. The first is that as the atmosphere becomes more "adverse", the differences in attenuations become less severe. The worst case shown on Fig. 1 is for a region of very high humidity, which from an operational condition is not considered severe. Perhaps unexpectedly, conditions of fog, dust, and snow (adverse for optical systems) create relatively little problems for MMW systems, especially since the particulates tend to stay close to the ground. In fact, the most adverse condition for MMW systems is probably hard rain which limits operational range from backscatter which will actually decrease slightly above 70 GHz.

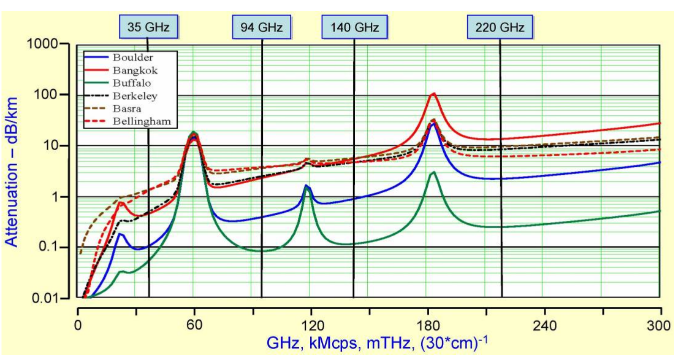

Figure 1 Atmospheric attenuation for different weather conditions represented by their locale.

The second major point is denoted by the four frequencies delineated: 35, 94, 140 and 220 GHz. These have become known as the operational "windows" in the atmosphere and some have even thought of them as quite narrow regions. Again, as the weather becomes more adverse, the windows actually become broader, allowing a more diverse selection of operating frequencies. But these specific frequencies, around which our current operational infrastructure is built, are based on the history of vacuum electronic (VE) devices. Each of the frequencies can be traced back to a specific enabling VE device realized for conceptual military systems around which the rest of the system, as well as test and measurement infrastructure were developed. In essence then, the current interest at 94 GHz in VE is based on a concept created in the 1960's that was based on a successful scaling by 10x a magnetron used extensively in X-Band systems.

Numerous conceptual military systems have been developed at these frequencies and have had limited technical success primarily from limitations in average power, coherent operation, and control devices for integration of RF components.

The primary reason for moving higher in the MMW region is to achieve capabilities similar to those available at lower frequencies on platforms where large antennas cannot be supported. Since antenna gain scales with the square of the frequency for a fixed antenna diameter and since radar and communications SNR scales with the gain squared, performance can increase despite increasing atmospheric losses. Figure two is an example calculation of the channel capacity of a ground to UAV system where the antenna sizes are kept constant and the system bandwidth is held at a constant bandwidth of 5% of center frequency. The condition of high humidity is the worst case for this scenario but the best performance is achieved when the frequency exceeds 100 GHz.

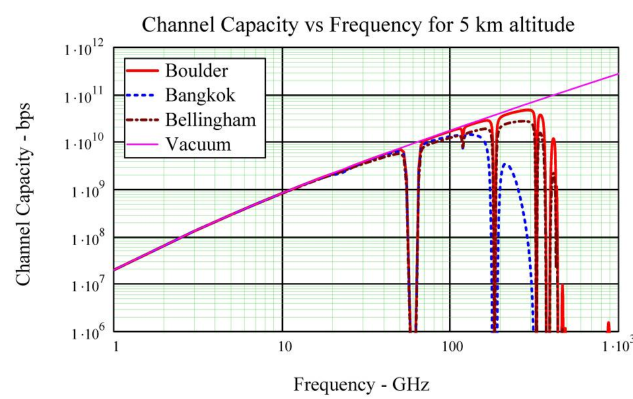

Figure 2 Channel capacity for a UAV to ground communication system assuming 5% bandwidth

Potential new applications of interest:
Other systems, such as a real time SAR for tactical targeting and terrain avoidance systems have been analyzed[ii] and have shown similar interesting results, although they are certainly all scenario and requirements dependent.

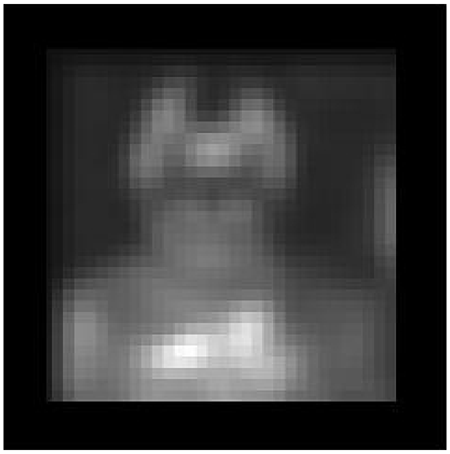

Figure 3 650 GHz image of person with a concealed metallic weapon

A recent area of interest has been in imaging at standoff ranges in order, for example, to enhance the safety of security personnel at check points. Numerous efforts, including the DARPA TIFT program, have been actively pursuing technology that will achieve reasonable image resolution, similar to Figure 3 [iii], at ranges of tens of meters. These programs are all realizing that the transmitter source may be the key limiting component. VE could certainly become the enabler once again at these frequencies, up to 1 THz.

What will Enable VE Above 100 GHz?

At microwave and lower millimeter-wave frequencies, vacuum electronic-based RF amplifiers have long been used for high power amplifier (HPA) circuits. But vacuum-electronic devices in this upper MMW range have been characterized by poor performance relative to such lower frequency VE circuits, and the size, weight, and cost of these systems provide insurmountable challenges to many potential military applications. These circumstances result from the unfavorable scaling physics of slow-wave structures and from the fact that the 200 GHz is close to or above the maximum frequency at which interaction structures can be readily machined using traditional machining methods (e.g., wire electron discharge machining). At 220 GHz, for example, the state-of-the-art output power is just a few watts, and the bandwidth is less than 1 GHz. In addition to their limited performance, the complexity and cost of conventionally-machined fabrication has greatly limited the availability of such devices.

A number of recent technology developments have offered a route to overcome these VE limitations. Most obviously, modern micro-fabrication methods such as Deep Reactive Ion Etching (DRIE) and LIGA are now capable of manufacturing slow-wave interaction structures at these frequencies with the required resolution and surface roughness characteristics. Further, significant progress has been made in the development of new cathode materials and structures. This is significant because, given appropriate compression optics, the unfavorable scaling of the slow-wave structures can be mitigated through the use of high aspect-ratio high-current density electron beams. Another significant enabling technology has been the recent advances in the development of solid-state MMICs at very high frequencies; such MMICs can potentially serve as the first amplification stage in a HPA power module. Finally, research ideas recently developed at other frequencies in slow-light and photonic (electromagnetic) band-gap structures may by analogy lead to advances in the gain, efficiency, bandwidth, and power performance of vacuum electronic devices.

DARPA has created a program entitled High-Frequency Integrated Vacuum Electronics (HiFIVE) which is challenging the community to demonstrate that these micro-fabrication technologies can be exploited to achieve an HPA of unprecedented performance and level of integration (Fig. 4). A central figure-of-merit will be power-bandwidth product, and the goal is to achieve, *at a minimum,* 500 W-GHz, and 220 GHz

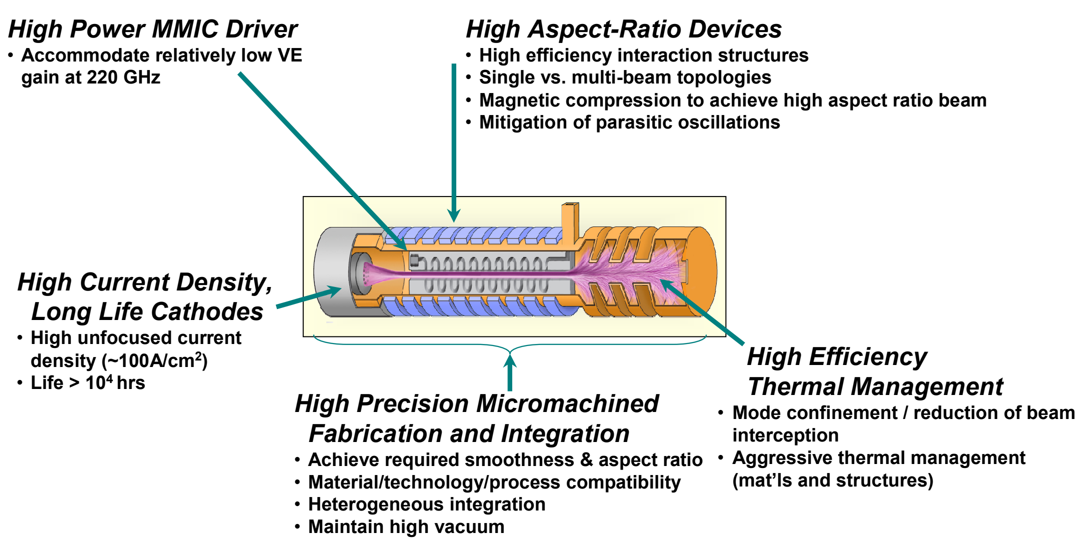

Figure 4 Technical challenges to achieving useful VE devices above 100 GHz

Conclusion

Vacuum electronics have served as an enabling technology for military systems since the first RF systems were created and will continue to into the future above 100 GHz. There is no wall that exists at 100 GHz that would prevent growth into the upper MMW region and there are numerous practical reasons for extending VE technology up to frequencies as high as 1 THz. This presentation has attempted to delineate some of the reasons and provide a description of technologies that will enable a new class of military systems.

References

[i] Wallace SPIE2006 Plenary talk
[ii] A&PS paper from 2006
[iii] IMS2007 paper